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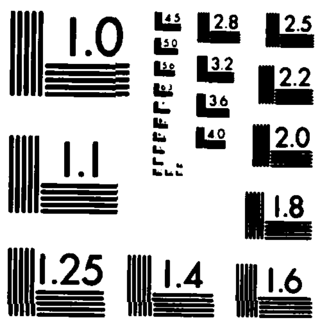
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A modification to a commercial radio-frequency power supply is outlined which enables the rf output power to be modulated over a broad frequency range (dc to 0.5 MHz). The modified power unit is used to drive an inductively coupled plasma of the kind utilized for elemental analysis. Applications of the modified unit include the study of energy storage and migration in the plasma and the modulation of atomic emission signals from elements present in chemical samples.

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MODIFICATION OF A PLASMA-THERM INDUCTIVELY COUPLED PLASMA SUPPLY TO ENABLE RF POWER MODULATION

by

R. E. Ensman, J. W. Carr, and G. M. Hieftje

Prepared for Publication

in

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Indiana University
Department of Chemistry
Bloomington, Indiana 47405

25 March 1983

A simple modification is described to enable amplitude modulation of the output of a commercial 5.0 kW inductively coupled plasma (ICP) power supply. Power modulation of an ICP might be useful in a number of practical and research situations. For example, amplitude modulation could be employed in a manner similar to optical chopping to improve signal detection efficiency in practical elemental analysis. Similarly, amplitude modulation permits the time-dependent energy flow in the plasma to be monitored.

It was this latter application that prompted the current instrumental development. We have determined (1) that modulated radiofrequency (RF) power produces in the discharge a modulated population of argon ions and electrons in the outer (skin) region. In turn, such species recombine to generate excited argon moieties that support the plasma and perhaps affect analyte excitation. The time-dependent movement of these energetic species can be followed by monitoring spatial patterns in the modulated populations. Correlation of these patterns with analyte emission and absorption maps then can be used to elucidate excitation mechanisms.

Amplitude modulation of a radiofrequency power oscillator is ordinarily accomplished by driving the plate of the vacuum tube in the last power amplifier stage. This method requires that the modulation driver be capable of delivering substantial amounts of power, the magnitude of which (at 100% modulation) approaches that delivered by the output stage of the RF generator, 5 kW in the present case. However, if the experiment permits the use of less than maximum RF output capability, less than 100% modulation, and some distortion of the modulation envelope, one can modulate instead the grid of the first buffer stage. In turn, this grid-bias

method of modulation can be accomplished by using commonly available, low-power test equipment and only slight modification of the RF power circuitry.

A 5 kW, 27.12 MHz ICP power supply (Plasma-Therm Inc., Kresson, NJ RF power supply model HFP 5000D) was modified to incorporate the modulation capability. In this modification one must disable the automatic power control circuit (detailed in Fig. 1) - with minor consequences, if an automatic load tuning system is being used - and substitute for it an external control-grid bias for the first buffer stage (amplifier tube #6146). The negative grid-bias-voltage source used in the modification was a Heath IP-17 supply (Heath Company, Benton Harbor, MI); however, any regulated voltage supply covering the range of -50 to -100 volts would be suitable. The amplitude modulation source, here an Interstate Electronics Corporation function generator (Anaheim, CA, model F-51), must be capable of isolated (floating) operation up to the voltage of the DC bias supply.

As shown in the portion of the HFP 5000D circuit diagram reproduced in Fig. 1, the DC bias voltage source and the modulation generator are connected in series and inserted between the wire removed from TB3-17 (the grid bias line for the 6146 buffer tube) and chassis common ground. The external bias-voltage supply is adjusted to the maximum negative voltage that causes no noticeable envelope distortion of the RF output; i.e. the negative-going peaks of the amplitude-modulation generator must not cause the buffer tube to cut off. Optimization of operating parameters will require some iteration among the amplitude of the modulation signal, the magnitude of the external bias voltage and the setting of the manual power-control found on the front panel of the HFP 5000D. Typical values leading to 30% modulation of a 1 kW power output (on the HFP 5000D chassis) are -85 V DC bias and 7 V_{p-p} modulation.

The RF signal and its modulation envelope can be monitored with a cathode-ray oscilloscope using a search coil placed in the vicinity of the RF load coil. A detectable signal was found to exist outside the shielded plasma enclosure. A useful self-supported search coil (5-7 cm in diameter) can be constructed of 5-10 turns of insulated 18-ga. wire. Use of a scope trigger signal, obtained from the modulation oscillator (cf. Fig. 1) will stabilize the oscilloscope trace of the RF modulation envelope. Typical traces of the RF signal are displayed in Fig. 2.

The amplitude-modulating input waveform can have almost any shape, some of which are shown in Fig. 2. In the present application the sine wave input is being used exclusively (Fig. 2A); however, square wave (Fig. 2B) and triangular wave (Fig. 2C) inputs will also produce a suitably modulated RF signal. In the case of the latter two waveforms, a smaller input signal (resulting in a smaller modulation) must be used if the RF output is to be relatively distortion free. Comparison of the function-generator sine wave and the power supply output shows very little distortion when the modulation amplitude is less than 30% of the 27.12 MHz peak-to-peak waveform. The degree of distortion of the RF signal at a fixed percentage of modulation is constant over the frequencies accessible with this modification. If modulation approaching 100% is desired, however, distortion of the RF signal is quite severe (Fig. 2D).

Exam..ation of the RF output waveform produced by a square-wave driver input reveals a spike at the leading edge of the pulse (Fig. 2B). The height of this spike, produced by switching of the signal generator, is dependent upon the switching speed of the power-supply electronics; if large enough, this spike could produce strong harmonics of the driving signal. In turn, such harmonics might be a source of serious RF inter-

ference for other radio service bands. Because our experiments employed exclusively sine wave modulation, the extent of this interference was not investigated. However, if square-wave modulation is desired, it is recommended that care be taken to adequately shield the modulated system, including supply, torch housing, and cables.

Amplitude modulation of the RF signal from DC to 50 kHz was possible using the modified circuit depicted in Fig. 1. However, the upper limit of the modulation frequency can be increased to 1 MHz by reducing the values of R16 and C22 to 56 ohms and 0.001 microfarads, respectively. The frequency response of the resulting system can be seen in Fig. 3; the degree of modulation begins to drop after 250 kHz but is usable up to 1 MHz.

It is important to recognize the effect of this modulation process on the frequency composition of the RF power output. When two frequencies are mixed, the product waveform contains the original frequencies plus components at their sum and difference. In accordance with Federal Communications Commission guidelines, the scientific or industrial frequency of 27.12 MHz can be used with a tolerence of 160 kHz. Taking the sum and difference frequencies into account, it is possible to modulate the RF generator from 0 to [illegible] kHz and still remain within FCC limits. Of course, this range applies only if the injected waveform is a sine wave and uncomplicated by the production of harmonic frequencies that might fall outside the recommended limits.

Fortunately, in our particular application it was never necessary to modulate the supply at frequencies above 30 kHz. Similarly, in most practical applications such as signal modulation, driving frequencies would seldom if ever exceed 1 kHz. Accordingly, RF transmission and interference should not be of concern. In other applications where higher

frequency operation is used, shielding should be employed and tested carefully.

Plasma ignition and operation of the modulated unit were possible with customary operating procedures. In fact, tuning parameters of the commercial impedance-matching network remained unchanged. Normal, unmodulated plasma operation could be restored at any time by setting the grid-bias-voltage supply to -61 V dc and reducing the output of the function generator to zero.

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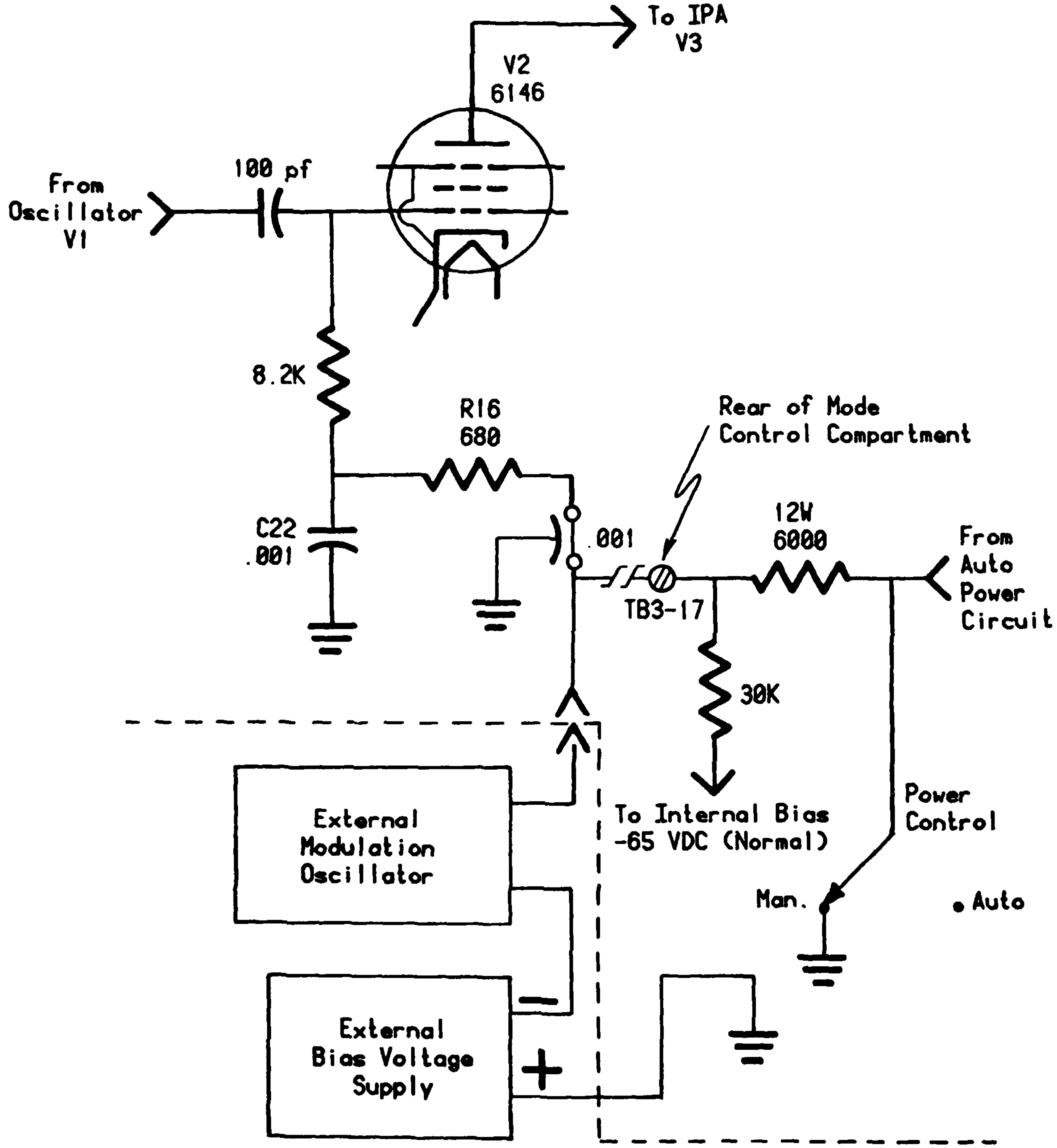
(1) J. W. Carr, J. W. Mills, and G. M. Hieftje. Submitted for publication, Spectrochim. Acta.

FIGURE CAPTIONS

Figure 1. Plasma-Therm HFP 5000D power system circuit diagram. Partial reproduction indicating the location of modifications and the connection of external equipment.

Figure 2. Input waveforms (left) and resulting modulated RF output (right) for (A) sine wave; (B) square wave; (C) triangular wave; and (D) high-voltage sine-wave modulation of RF supply.

Figure 3. Frequency response of the modulated RF supply of Fig. 1. Input signal held at fixed level.


To IPA
V3
V2
6146
From
Oscillator
V1
100 pf
8.2K
R16
680
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Control Compartment
C22
.001
.001
12W
6000
From
Auto
Power
Circuit
TB3-17
30K
To Internal Bias
-65 VDC (Normal)
Power
Control
Man.
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External
Modulation
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−
+

Fig 1

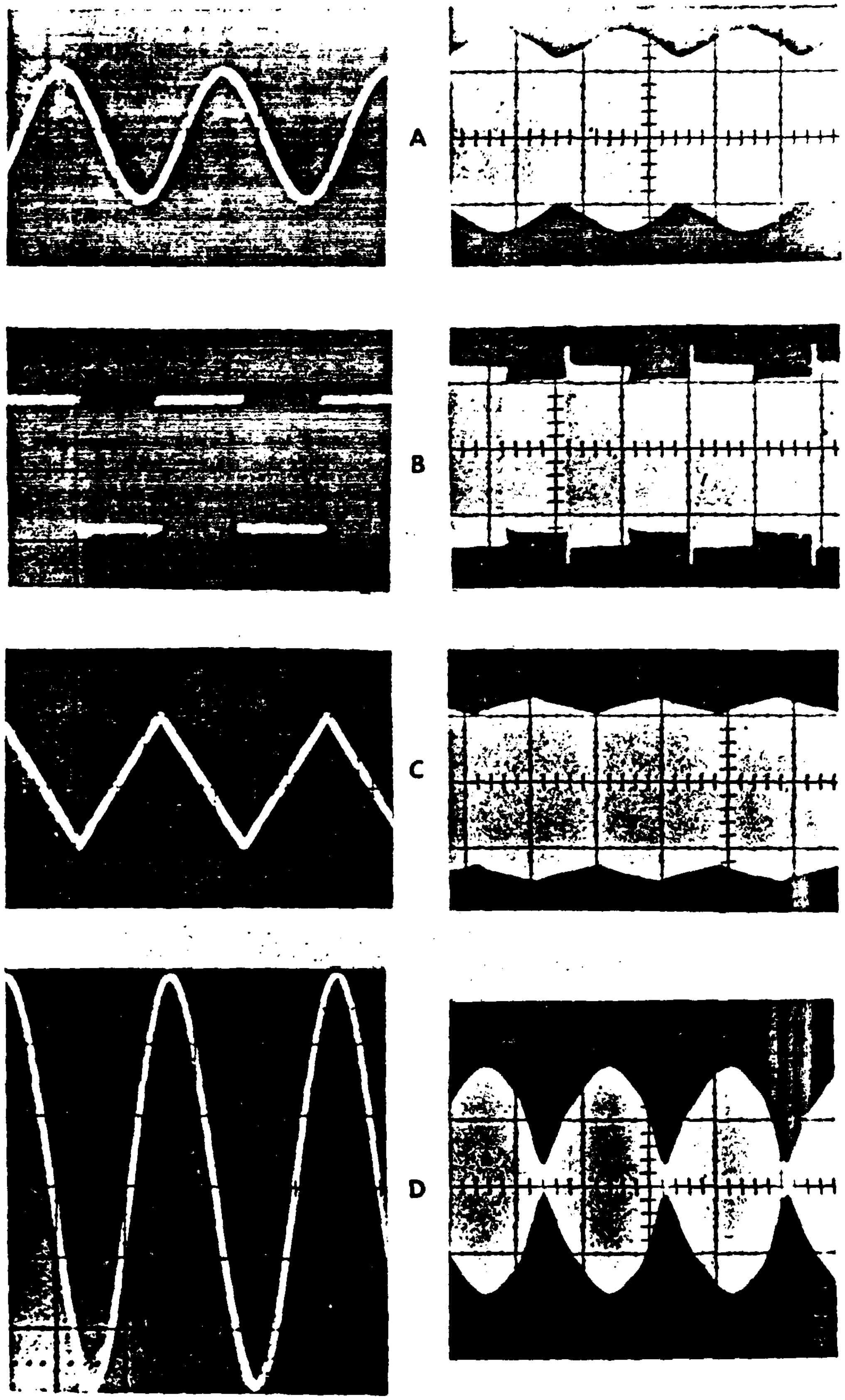

Fig 2

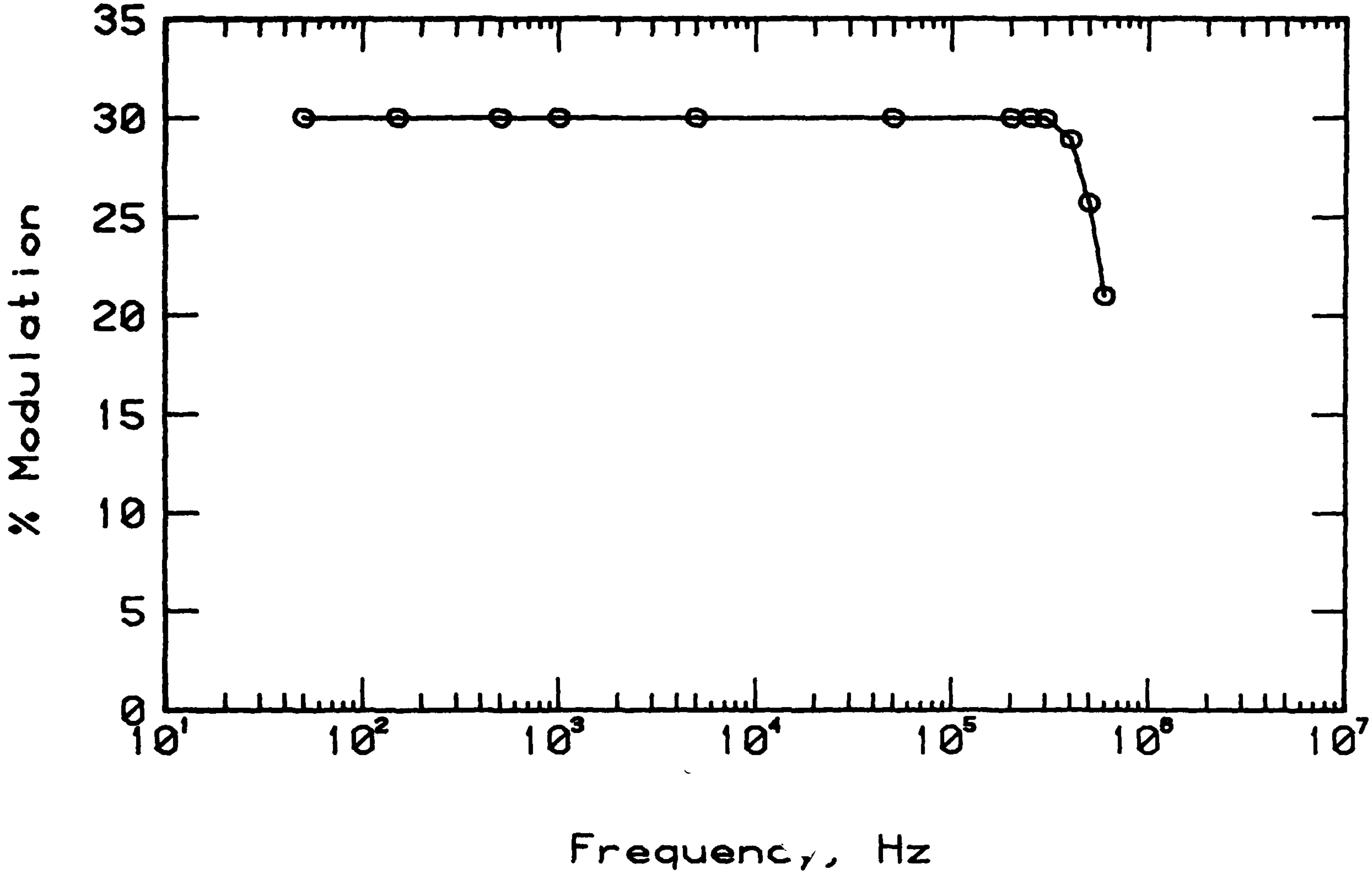
% Modulation
35
30
25
20
15
10
5
0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Frequency, Hz

Fig 3

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